The paper was presented at the Eleventh Meeting
“New Trends in Fatigue and Fracture” (NT2F11)
Polignano a Mare, Italy, 3–6 July, 2011

Radomir Jovičić [1], Aleksandar Sedmak [1], Stojan Sedmak [2], Ljubica Milović [2], Katarina Jovičić [2]

LEAKAGE OF AN AUSTENITIC STEEL CO_2 STORAGE TANK

CURENJE POSUDE ZA SKLADIŠTENJE CO_2 OD AUSTENITNOG ČELIKA

Originalni naučni rad / Original scientific paper
UDK /UDC: 621.642.34:669.15-194.56
Rad primljen / Paper received: 21.01.2012

Adresa autora / Author's address:
[1] University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia, asedmak@mas.bg.ac.rs
[2] University of Belgrade, Faculty of Technology and Metallurgy, Belgrade, Serbia

Keywords
- storage tank
- austenitic steel
- welded joint
- crack
- operational safety

Abstract

After the occurrence of water droplets on the manhole outer wall of a storage tank for carbon dioxide, by detailed inspection, a net of cracks is detected in the manhole flange, close to the welded joint between the flange and manhole mantle. Since the droplets are found on the outer side, it is concluded that the through cracks are in question. The analysis of the number and the size of cracks, form and dimensions of manhole cracked segment, the properties of the applied material and stress state has lead to the conclusion that operational safety of the tank is endangered. In order to solve the problem, the damaged zone had to be eliminated and the shape of the manhole neck needed to be re-designed. After performed repairs, the storage tank could be put into operation again.

Ključne reči
- posuda za skladištenje
- austenitni čelik
- zavareni spoj
- prslina
- sigurnost u radu

Izvod

Posle pojave vodenih kapi na spoljašnjem zidu otvora za reviziju posude za skladištenje ugljen dioksida, detaljnom inspekcijom je otkrivena mreža prslina na prirubnici revizionog otvora, blizu zavarenog spoja između prirubnice i zida revizionog otvora. Pošto su kapljice uočene na spoljašnjoj strani, zaključuje se da su u pitanju prolazne prsline. Analizom broja i veličine prslina, oblika i dimenzija segmenta naprslog revizionog otvora, osobina primenjenog materijala i naponskog stanja, su doveli do zaključka da je radna sigurnost posude u opasnosti. Da bi se rešio ovaj problem, oštećena zona je morala da se ukloni, a oblik vrata revizionog otvora je morao da se rekonstruiše. Nakon obavljenih popravki, posuda za skladištenje je ponovo puštena u rad.

INTRODUCTION

During the testing of storage tank for liquefied carbon dioxide by proof pressure droplets of water had been revealed on the outer wall of its manhole, /1/. The storage tank is of cylindrical form, thermally insulated, 12.5 m^3 in volume. The mantle and tank lids are produced of micro alloyed steel P 460NL1, 14 mm in thickness. The lowest operating temperature of the tank is –55°C, the highest operating pressure 30 bar, the proof pressure test 39 bar. The storage tank is classified as II class of pressure vessels. A general view of tank and position of a manhole is presented in Fig. 1.

After removing the thermal insulation from the manhole, the moisture is located around the welded joint between the mantle and flange neck. The manhole consisted of mantle, produced of P 460NL1 steel, 10 mm thick, and a flange casting of high alloyed austenitic steel X10CrNi18.10, /2/. The manhole and welded joint at which the leakage is detected are presented in Fig. 2.

According to Ref. /2/, the flange and the manhole are welded by shielded manual arc welding (SMAW), using high alloyed austenitic consumable INOX 29/9.

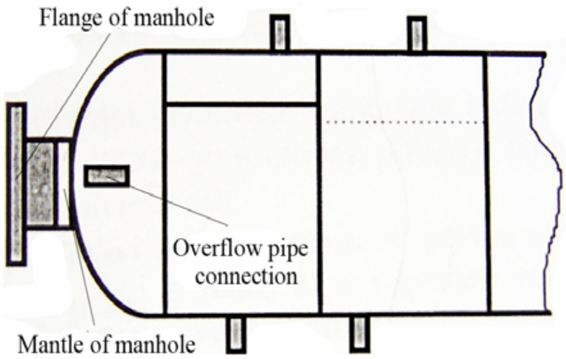

Figure 1. General view of tank for liquefied CO_2 storage with the position of the manhole.
Slika 1. Opšta shema posude za skladištenje tečnog CO_2 sa položajem revizionog otvora

Figure 1. Manhole and welded joint where leakage occurred.
Slika 1. Revizioni otvor i zavareni spoj, gde se pojavilo curenje

EXPERIMENTAL RESULTS

The welded joint between the flange and manhole mantle had been performed as a butt joint. Flange necking towards the welded joint ended by a cylindrical part of diameter and thickness that are equal to the diameter and thickness of the manhole mantle, of width 30 mm, /1/. The cracking network had been detected in this cylindrical part of the flange neck in a clearly limited zone.

All cracks are located in the zone starting about 3 mm from the fusion line of the weld metal and ending on the transition from the cylindrical to the conical part of the flange neck. The orientation of cracks is approximately in the manhole axis direction, i.e. the tank’s axis. Crack density is different on the joint periphery, ranging from very expressed in a zone about 250 mm in length, to extra small in the zone covering about one half of joint periphery. In the zone of high crack density, they cross each other, producing a network. Mostly they extend 25 to 27 mm in length. In the zone of individual cracks, only short cracks, 1 to 2 mm long, are detected.

After emptying the tank and opening the manhole, its inner side was tested. On the inner side two larger pores are found and also individual cracks, 1 to 2 mm in length. Figures 3 and 4 present the cross section through the middle of cylindrical part of the flange neck, in fact through the middle of the damaged zone.

The cross section of the middle of the zone with the highest cracking density is shown in Fig. 3. A large number of cracks, approximately perpendicular to the flange surface, are visible. Testing by dye penetrants through the zone axial section indicates a large number of cracks penetrating to different depths, some of them through the thickness.

Figure 3. Cross section of the middle of zone with the highest cracking density.
Slika 3. Poprečni presek srednje zone sa najvećom gustinom prslina

Figure 4. Two pores on inner side of manhole present the initial part of through cracks.
Slika 4. Dve pore na unutrašnjoj strani revizionog otvora predstavljaju inicijalni deo prolaznih prslina

In Fig. 4 the cross section close to the pores detected on the inner side of a manhole is presented. Two pores, which are in fact the continuation of pores detected on the inner side of the manhole, can be clearly recognised. Most intensive leakage on the outer side of the manhole is revealed just opposite of these pores, since they are followed by cracks, penetrating to the outer surface of the tank.

The cylindrical part of the flange and the welded joint between the flange and mantle of a manhole are presented in Fig. 5. This part is cut out from a manhole in the repairing procedure. The flange is separated, first together with the welded joint, by applying gas flame cutting, and then the segment with cracks is separated by machining. The lower edge in Fig. 5 is uneven as a residue of machining by lathe.

Figure 5. Cylindrical part of the flange and welded joint between the flange and mantle of the manhole.
Slika 5. Cilindrični deo prirubnice i zavarenog spoja između prirubnice i zida revizionog otvora

DISCUSSION

According to the appearance, number and location, the detected cracks are likely to be that occurring in austenitic steels due to intercrystalline corrosion. Since the flange outer side is in contact with air, i.e. the flange material is not in contact with an aggressive medium, there is no condition for the development of intercrystalline corrosion. It might be concluded that the cracking has occurred due to some other mechanism of brittleness, typical for the steel X10CrNi18.10. The chemical composition of the steel X10CrNi18.10 is given in Table 1, and its tensile characteristics in the as-casting condition are given in Table 2, /3/.

Table 1. Chemical composition of X10CrNi18.10 steel.
Tabela 1. Hemijski sastav čelika X10CrNi18.10

	C	Si	Mn	Cr	Ni	Structure
G-X10CrNi18 8	≤ 0.12	≤ 2.0	≤ 1.5	17.0–19.5	8.0–10.0	austenite

Table 2. Tensile characteristics of X10CrNi18.10 steel in as-casting condition.
Tabela 2. Zatezne karakteristike čelika X10CrNi18.10 u livenom stanju

Cast steel	Yield strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation A (%)	Contraction Z (%)
G X10 CrNi 18 8	180	450–650	20	–

From Table 1 it can be seen that the content of C is high, and that there are no stabilizing elements, like Nb and Ti. According to /4/, after fast cooling from temperature above 900°C to the room temperature, the X10CrNi18.10 steel obtains an austenitic structure. However, re-heating to temperatures lower than 900°C causes the segregation of δ-ferrite and carbide $(Cr,Fe)_4C$, and under a certain condition, also of intermetallic compound, FeCr-σ phase. Separation of carbide is very intensive in the temperature range 450-850°C and starts in the steel X10CrNi18.10 after being held at these temperatures even for less than one minute, /3/. Thus, one may can conclude that the zone with segregated carbides might be formed close to the welded joint. The width of this zone depends on the width of the zone at which the material has been heated to the temperature between 450 and 850°C for a time longer than one minute. That means that carbide will not dissolve in the heat-affected-zone (HAZ) region between fusion line and the line where the temperature was above 850°C. Carbides are primarily dissolved at the austenite grain boundaries, in the form of an intermittent network. With temperature increase and longer heating time, the carbides have formed a continuous network at grain boundaries, and then started to dissolve also inside austenitic grains.

The brittleness of X10CrNi18.10 can also be caused by structural changes during heating at temperatures about 475°C and also due to the formation of σ phase dissolved during heating in the temperature range 550-875°C. So, these phases occurred in the same temperature interval as carbides, but for their formation, a longer time is necessary.

There are only few data on the effects of brittle phases on strength, plasticity and ductility of the considered steel. They generally claim that the presence of carbides reduces plasticity and ductility of the steel, and that the σ phase already in a small amount significantly reduces the steel ductility.

The positions of zones in which segregations of brittle phases and zones are expected (but not segregation of brittle phases in the HAZ between flange neck and the mantle) coincided with the positions of zones in which the cracks are detected and that in which cracks had not been detected during the investigation of this joint. Based on that, it is possible to assume that the cracks occurrence is connected with the occurrence of brittle phases, primarily carbides.

Investigation has shown that, in the zone of the highest crack density, all cracks are located in clearly defined regions and all of them are oriented approximately along the tank axis. Therefore, the following crack initiation and growth mechanisms can be proposed. Microcracks are formed around carbide inclusions. Under applied tensile stresses “the bridges” of the austenitic material are elongated and broken, enabling crack coalescence and their growth. The highest tensile stresses in the cracked zone are hoop stresses, affecting the cracks to grow in the direction of the tank axis. Crack propagation will be arrested at the boundaries of the zone with dissolved carbides, because crack tip enters material of higher plasticity. The conditions for crack growth are still present in the thickness direction. One can expect that by an increase of the number of broken metal “bridges”, the applied stresses will locally increase, so the number of through cracks will increase, intensifying the leakage.

It is concluded that the detected cracks affect the safety operation of the tank, and hence retrofitting is required /5-9/. The only economical way for retrofitting is complete elimination of the damaged zone. The same flange with the removed dissolved carbides is now re-welded with the manhole mantle, and the applied welding procedure has prevented the precipitation of brittle phases.

CONCLUSIONS

Cracks in the flange made of austenitic material had occurred due to the brittleness induced by the segregation of the brittle phases, mostly carbides, influenced by the welding heat cycle in the welded joint, specifically in a region between the flange and manhole mantle.

The widths of the zone where the brittle phases occur limit the crack lengths from being oversized. The only possible direction of crack growth is through the wall full thickness, causing the leakage of the storage tank.

The leakage can be avoided using low carbon steels and steels alloyed with titanium and niobium, such as austenitic steels, which have lower tendency to carbide forming. The welding technology also has to ensure that the holding time of the austenitic material in the temperature range in which the brittle phases segregate must be shorter than the critical time for their segregation.

REFERENCES

1. Technical report on recuperation and inspection of liquid carbon dioxide reservoir in "Minakva" – Novi Sad, University of Belgrade, Faculty of Mechanical Engineering, 1998. (in Serbian)
2. Technical documentation for liquid carbon dioxide reservoir, Energoinvest TPO, Gorazde, 1979. (in Serbian)
3. Limpel, I., Heat resistant, stainless and chemically resistant steels, weldability, welding methods and technologies, Welding Institute, Ljubljana, 1987.
4. Schumann, H., Metallographie, Wiley-VCH Verlag GmbH, 1981.

International Conference on Damage Mechanics (ICDM)

25-27 June 2012, Belgrade, Serbia

Objectives

The main objective of the International Conference on Damage Mechanics (ICDM) is to bring together leading educators, researchers and practitioners discussing and exchanging ideas on recent advances in damage and fracture mechanics. Since 1958, following the pioneering work of L.M. Kachanov, the theory of damage mechanics has in particular made significant progress and established itself capable of solving a wide range of engineering problems. This inaugural conference will provide a forum for scientists and practicing engineers alike to present the latest findings in their research endeavor and at the same time to explore future research directions in the fields of damage and fracture mechanics. The inauguration of the ICDM is also considered timely as it coincides with the 20th anniversary of the founding of the International Journal of Damage Mechanics.

Conference Topics

Specific topics of interest include, but are not limited to, the following:

- Multiscale damage and fracture characterizations
- Nano-micro damage mechanics and fracture in composites and bio-materials
- Continuum damage mechanics
- Computational damage mechanics and fracture
- Experimental characterization and validation of damage and failure mechanisms
- Diagnosis or quantification of material damage and failure
- Dynamic damage, fracture and failure
- Applications to metal forming and in-service structural integrity
- Applications to concrete, cementitious composites, and geomaterials
- Applications to nano-materials and bio-materials
- Applications to aging infrastructures and structures

Important dates

Deadline for submitting one page abstract: October 1st, 2011
Notification of abstract acceptance: November 1st, 2011
Deadline for submission of optional full paper and mandatory early registration fees for authors: January 31st, 2012

Conference Chairmen

Chi L. Chow, University of Michigan, Dearborn, USA
J. Woody Ju, University of California at Los Angeles, USA
Dragoslav M. Šumarac, University of Belgrade, Serbia

Local Organizing Committee

Dragoslav Šumarac (Chair), Nataša Trišović, Maja Todorović, Dragoslav Kuzmanović, Sreten Mastilović

International Scientific Committee

J.L. Chaboche (France), Olivier Allix (France), Holm Altenbach (Germany), Elias C. Aifantis (Greece), Yilong Bai (China), Michal Basista (Poland), Zdenek P. Bazant (USA), Joseh Betten (Germany), Wolfgang Brocks (Germany), Michael Brunig (Germany), Alberto Carpinteri (Italy), Diego Celentano (Chile), E.P. Chen (USA), Zhen Chen (USA), L.R. Dharani (USA), Andre Dragon (France), Emmanuel E. Gdoutos (Greece), Vencislav Grabulov (Serbia), Jovo Jarić (Serbia), Iwona Jasiuk (USA), Reinhold Kienzler (Germany), Kikuo Kishimoto (Japan), Djimedo Kondo (France), Shiro Kubo (Japan), Pierre Ladeveze (France), Soon-Bok Lee (Korea), Jean Lemaitre (France), Xikui Li (China), Jianguo Lin (UK), Y.W. Mai (Australia), D.L. McDowell (USA), Sreten Mastilović (Serbia), Siniša Mesarović (USA), Milan Mićunović (Serbia), Ružica Nikolić (Serbia), Martin Ostoja-Starzewski (USA), Jwo Pan (USA), Marko Rakin (Serbia), Ekkehard Ramm (Germany), Khemais Saanouni (France), Bernhard Schrefler (Italy), Raju Sethuraman (India), Pol Spanos (Greece), Lizhi Sun (USA), R. Talreja (USA), T.E. Tay (Singapore), Yutaka Toi (Japan), Viggo Tvergaard (Denmark), Rade Vignjević (UK), George Z. Voyiadjis, (USA), B.L. Wang (Australia), Shou Wen Yu (China), Peter Wriggers (Germany)

Conference Secretariat

Serbian Chamber of Engineers
Kneza Milosa, St. 9/1 11000 Belgrade
Tel. +381-11-3248-585
http://www.icdm.rs
e-mail: info@icdm.rs

Accommodation and Venue

Venue and accommodation is organized in cooperation with hotel Holiday Inn Belgrade:
74 Spanskih Boraca
Belgrade 11070 Serbia
Hotel Front Desk: 381-11-3100000
Hotel Fax: 381-11-3100100
http://www.holidayinn.com